

PHENIX Flow at Low Energies

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RHIC

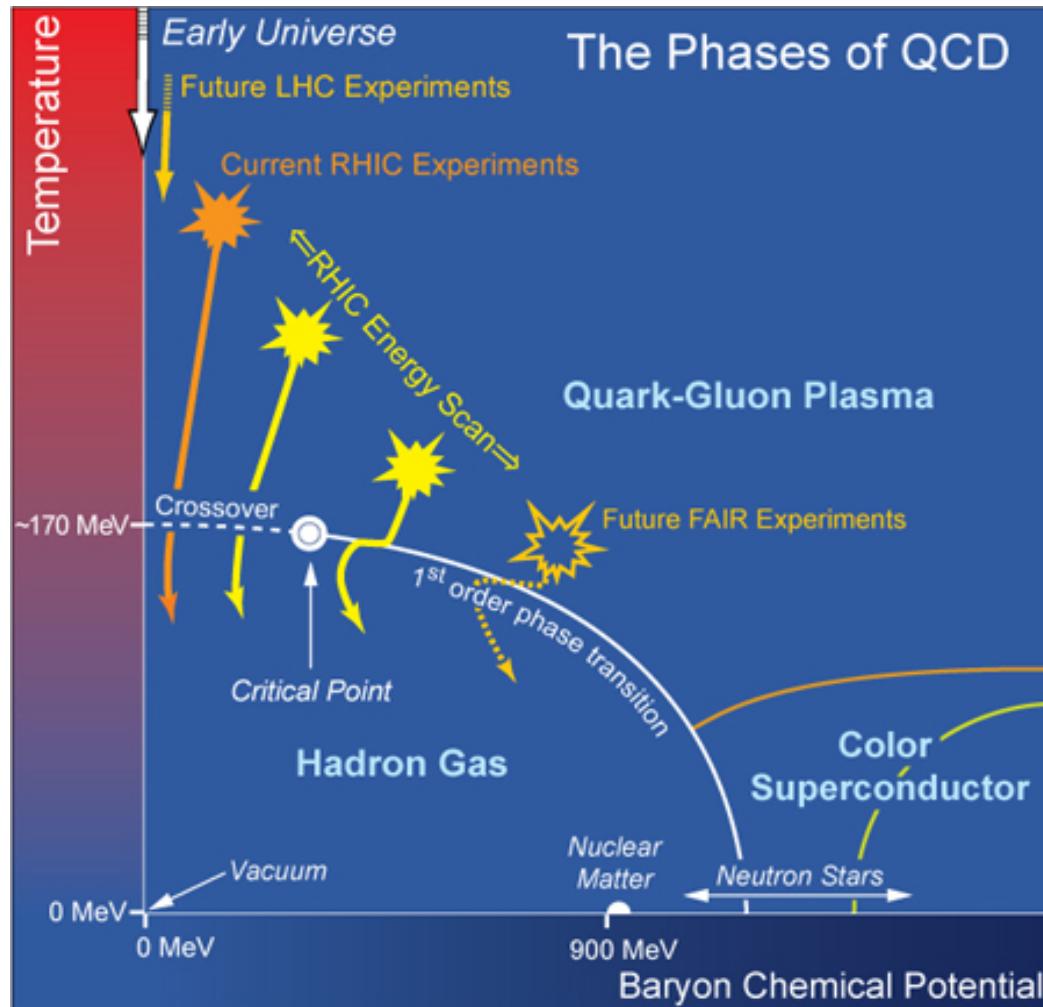
At Brookhaven National Lab's Relativistic Heavy Ion Collider, physicists from around the world study what the universe may have looked like in the first few moments after its creation. What scientists learn from RHIC may help us understand more why the physical world works the way it does, from the smallest subatomic particles, to the largest stars.



Outline

- RHIC Energy Scan
- PHENIX Flow at Low Energies
 - Charged Particle Flow Measurements
 - PIDed Hadron Flow Measurements
- Further discussion and Summary

Schematic QCD Phase Diagram



A crucial task in experimental heavy ion collision is to map out the QCD phase diagram.

RHIC experiments at beam energy 200GeV showed that QGP is created and cools down to hadron gas via **crossover** transition.

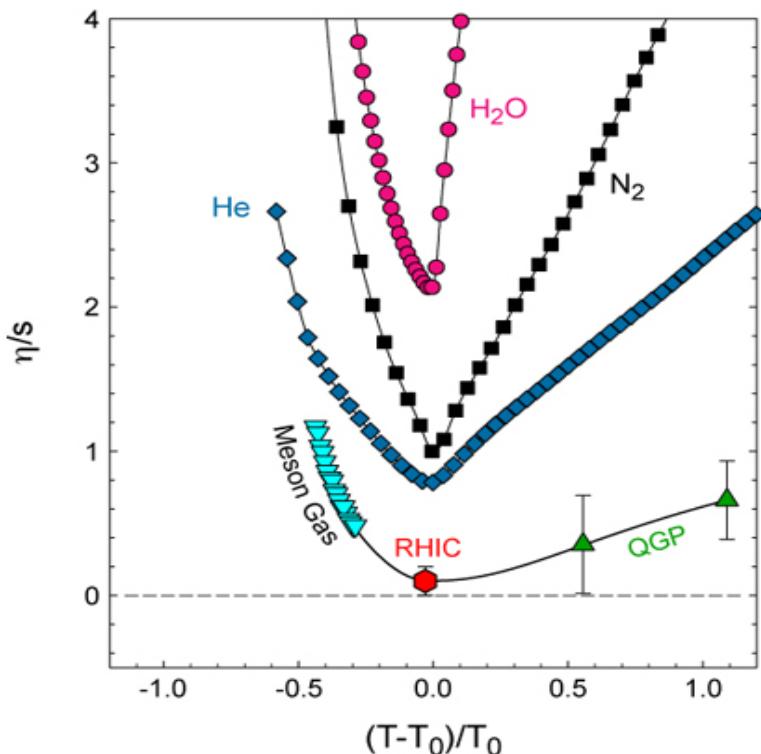
RHIC has embarked an beam energy scan (BES) program to:

- Locate the QGP-Hadron Gas **phase boundary** and **critical point**.
- Obtain properties of nuclear matter in each phase.

Why Flow Measurements?

Flow coefficients measurements

critical point search ?



Equation of State (EOS)

bulk viscosity(ζ), shear viscosity(η),
specific viscosity(η/s) of sQGP and
their temperature dependence

partonic vs. hadronic viscosity

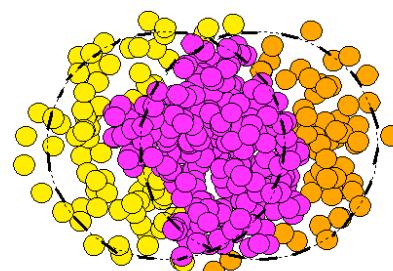
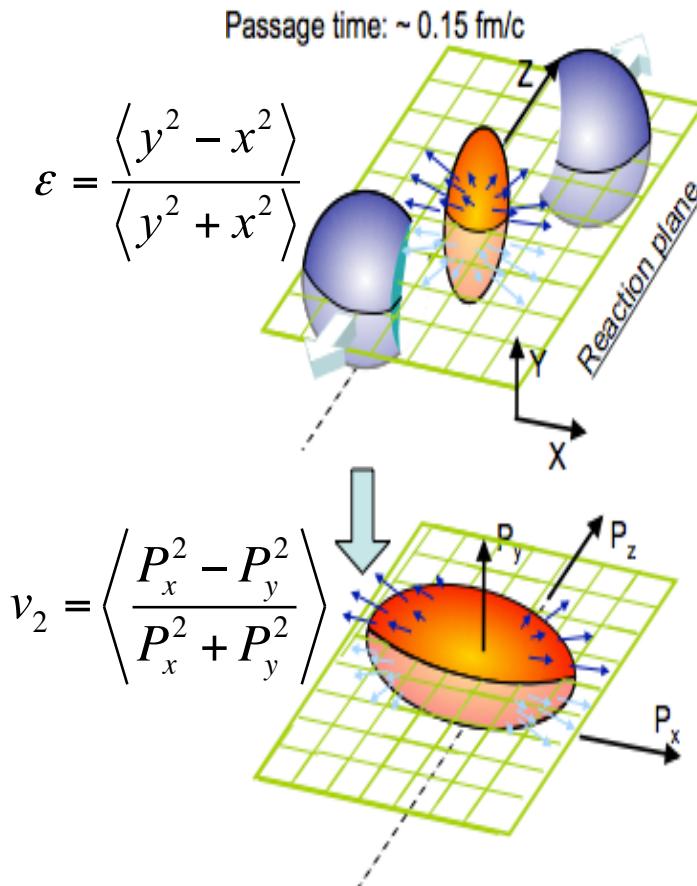
The role of fluctuations and initial
conditions

Flow measurements serve to find invaluable experimental constraints which can help resolve these issues listed above, and to locate the critical point.

The Flow Probe

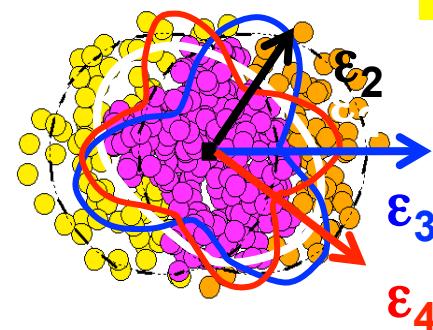
- Initial spatial fluctuations of nucleons result in higher moments of deformations, each with its own orientation.

Alver, Roland, Staig, Shuryak,



For smooth profile $\varphi \rightarrow \varphi + \pi$

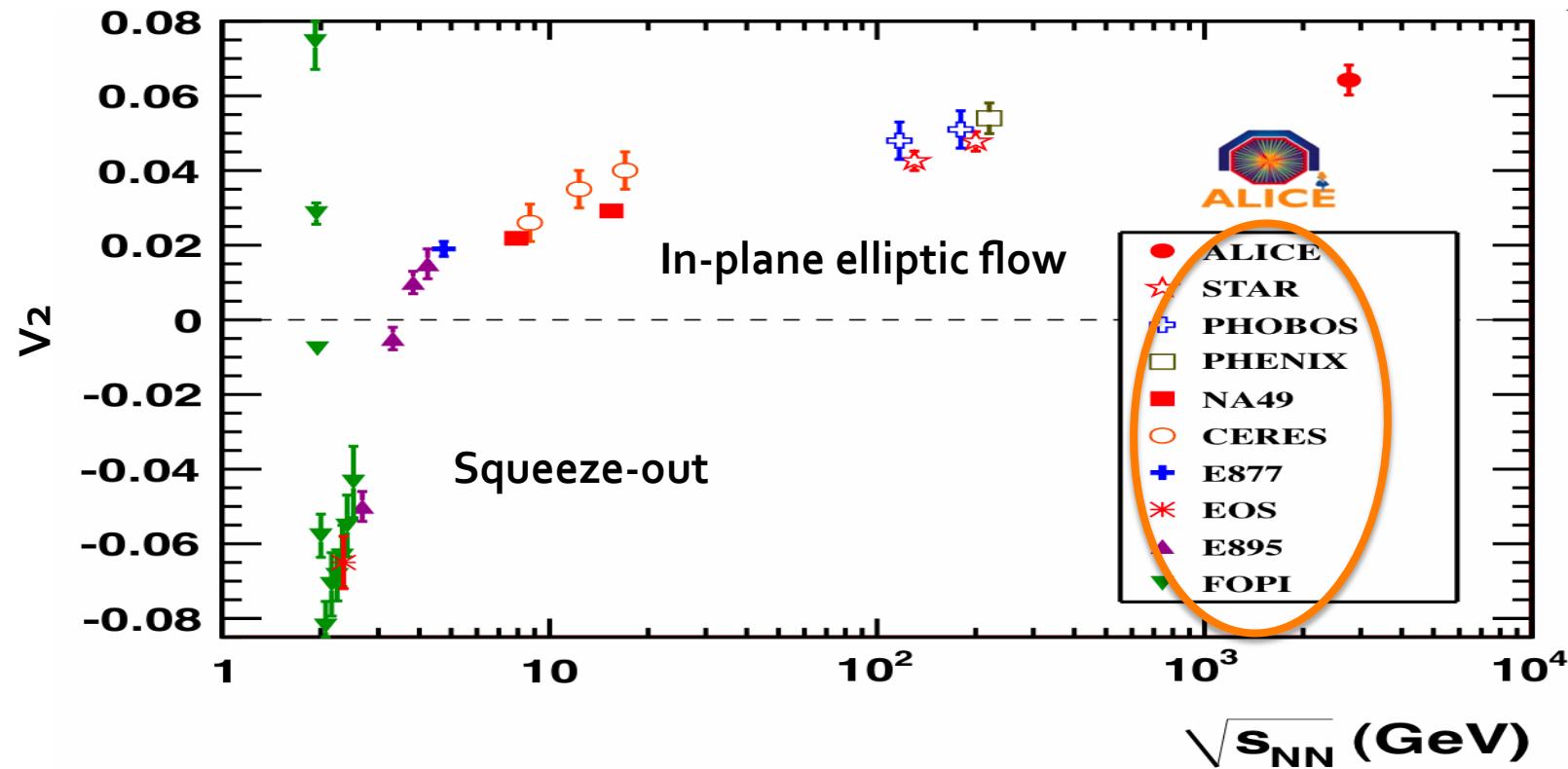
Odd harmonics = 0



For "lumpy" profile $\varphi \neq \varphi + \pi$

Odd harmonics $\neq 0$

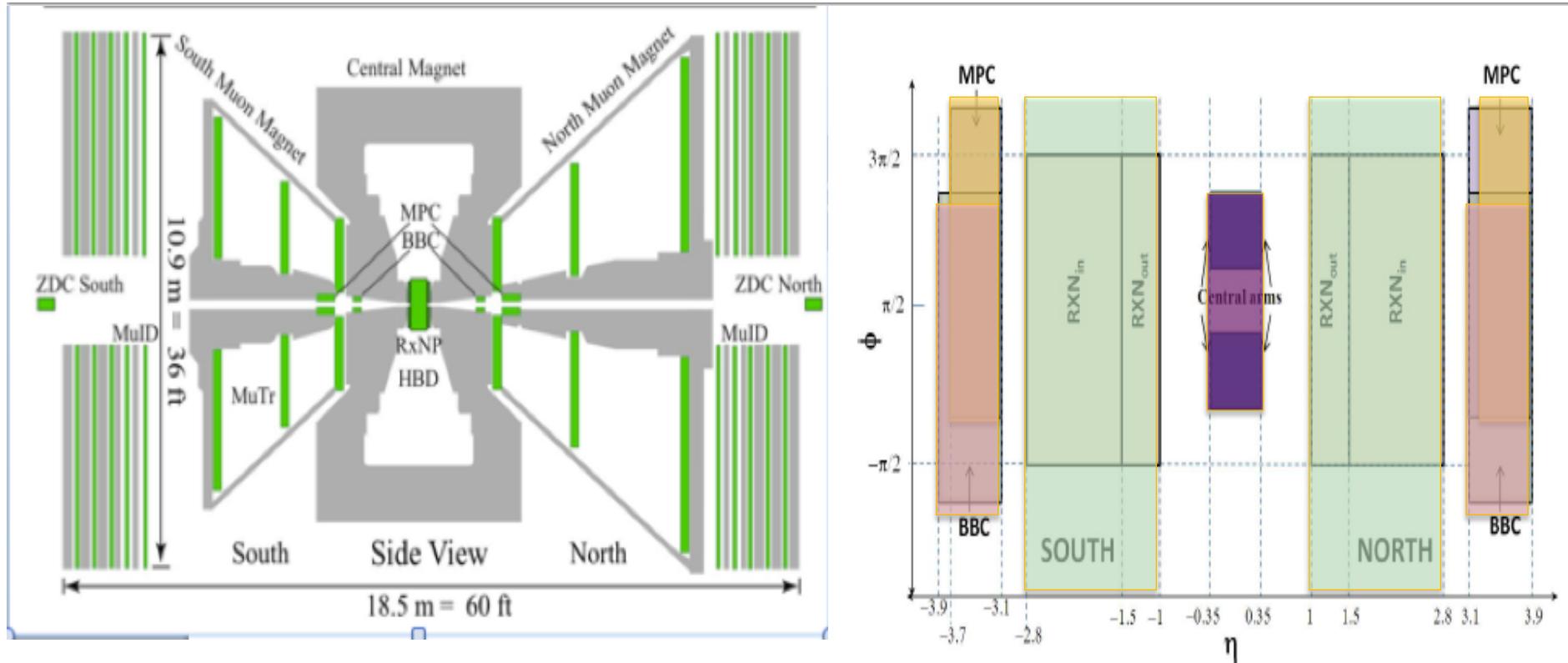
Why energy scan?



At which point flow at partonic level does not hold any longer?

What is the specific viscosity (η/s) at these beam energies?

Flow Measurement in PHENIX



Wide range of η coverage with several R.P. detectors

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1} 2 v_n \cos(n(\phi - \Psi_n))$$

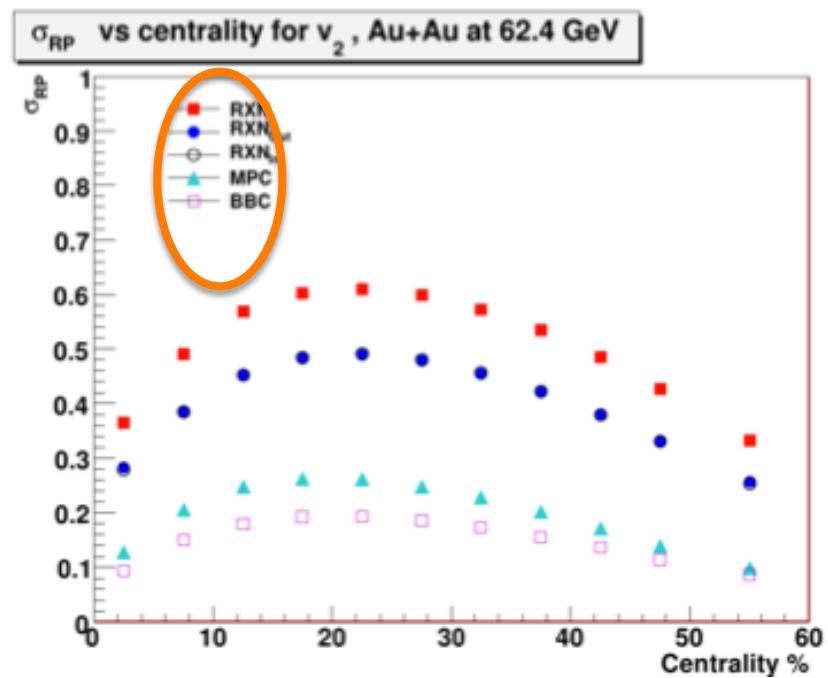
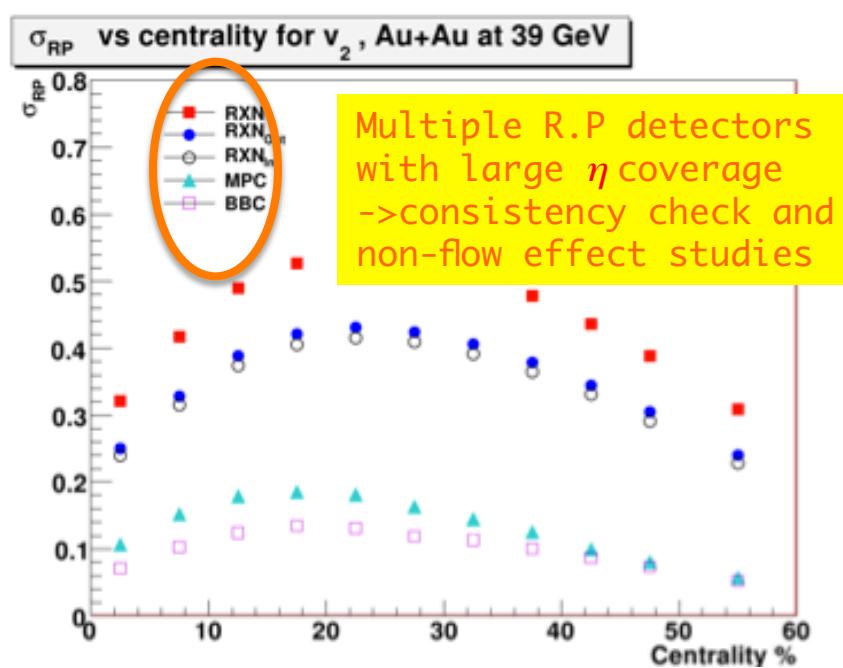
$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle, n = 1, 2, 3, \dots$$

$$\begin{aligned} \Psi_n & \text{ RXN } (|\eta|=1.0 \sim 2.8) \\ & \text{ MPC } (|\eta|=3.1 \sim 3.7) \\ & \text{ BBC } (|\eta|=3.1 \sim 3.9) \end{aligned}$$

*standard EP technique with systemic studies
using various R.P. detectors*

R.P detectors Resolutions

- Correlate hadrons in central arms $|\eta| < 0.35$ with event plane (RXN, etc), corrected by its dispersion reference to reaction plane(Resolution)



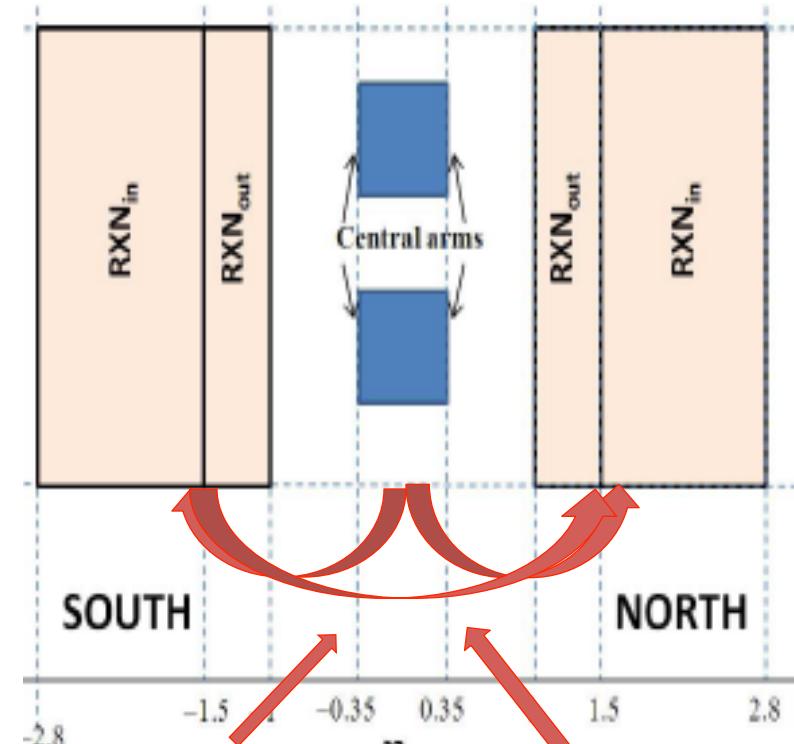
- (2nd order) RXN has the best resolution at each beam energy $v_n = \frac{v_n^{\text{obs}}}{\text{Res}\{\Psi_n\}} = \frac{\langle \cos n(\phi - \Psi_n) \rangle}{\langle \cos n(\Psi_n - \Psi_{RP,n}) \rangle}$
- Resolution drops dramatically as collision goes to more peripheral or central

2 particle correlation(2pc) method

- Served as completely independent complimentary crosscheck to EP method results
- Pair-wise $\Delta\phi$ distribution:

$\frac{dN}{d\Delta\phi}$ Does this give same results as E.P method?

- Correlate long-range(large $\Delta\eta$) two particles to reduce non-flow effect:
 - Track #1 : central arm
 - Track #2: signal in RXN detector
- If flow dominates, $v_{n,n}$ is expected to factorize into product of two single flow v_n
- v_n (cent) from “fixed-centrality” correlation in RXN_S and RXN_N signals
- $v_n(p_T)$ of CentralTrack extracted

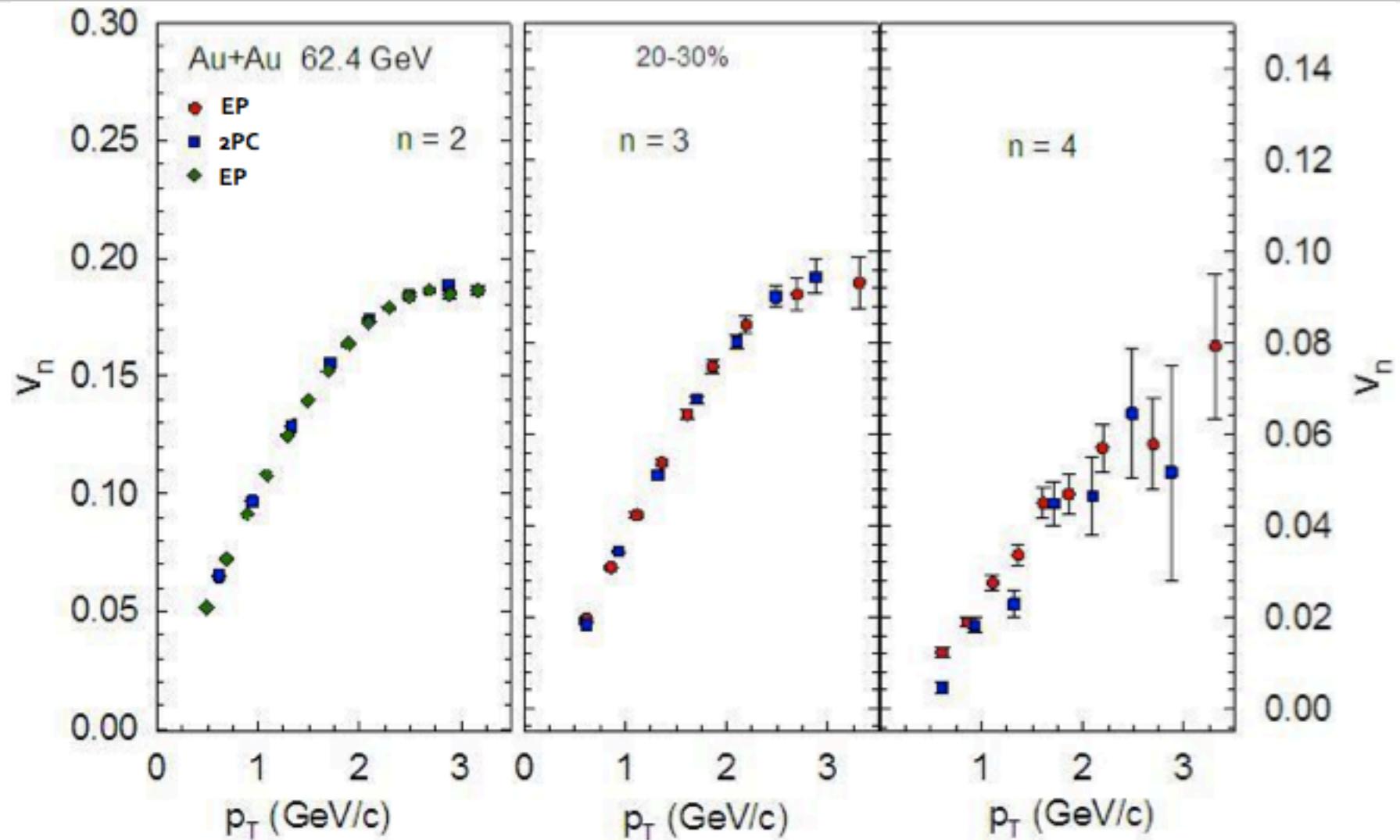


$$v_{n,n}(P_T^a) = v_n(P_T^a) v_n^{RXN}$$

$$v_n^{RXN} = \sqrt{v_{n,n}^{RXN-S+N}}$$

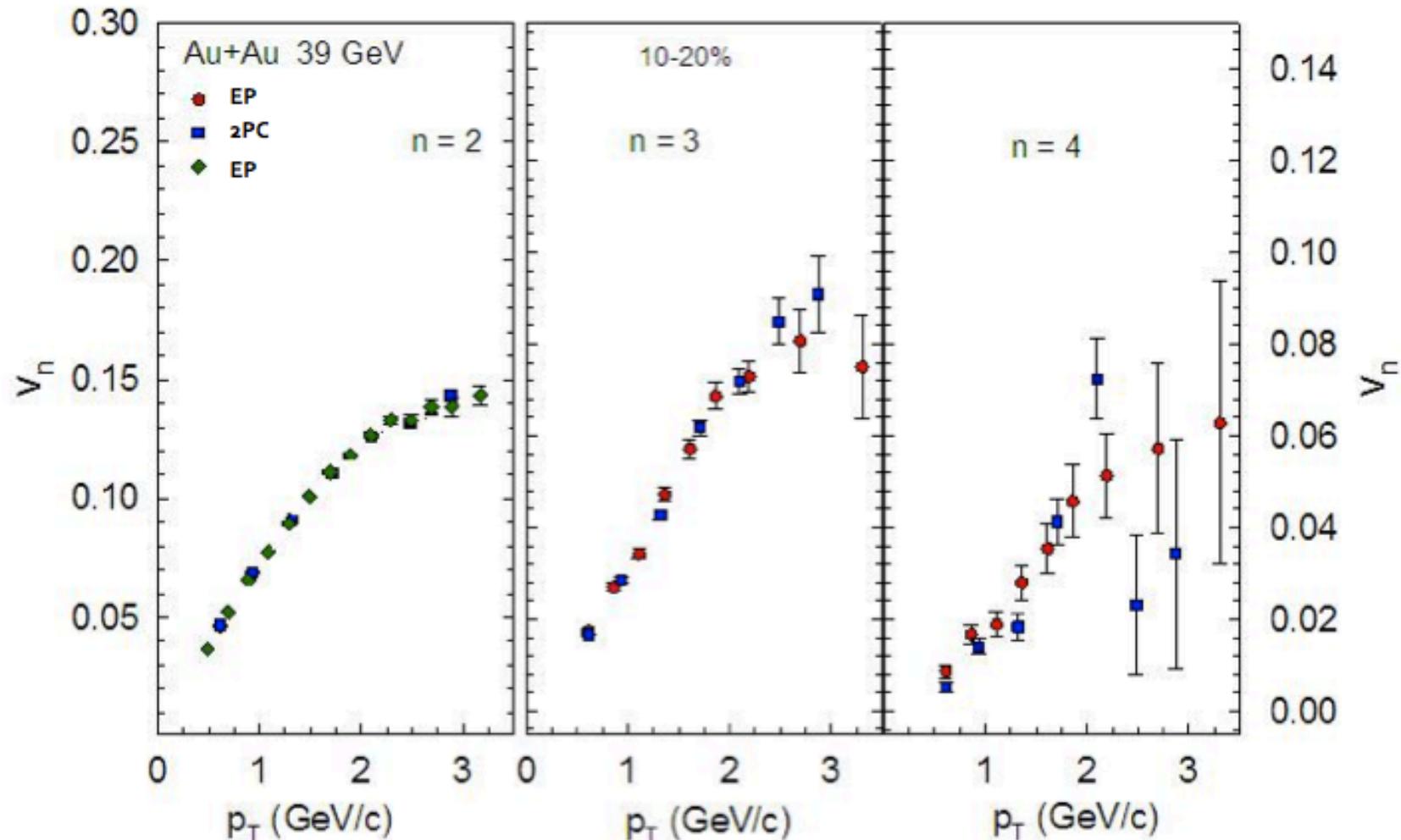
$$v_n(P_T^a) = v_{n,n}(P_T^a) / \sqrt{v_{n,n}^{RXN-S+N}}$$

Good Consistency between EP and 2PC(62.4 GeV)



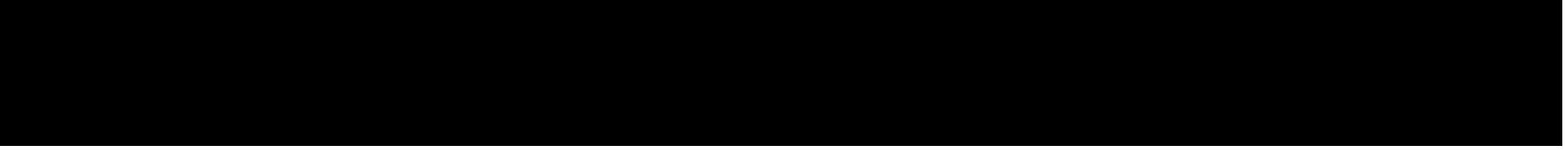
2PC gives the same flow results as EP method

Good Consistency between EP and 2PC(39GeV)



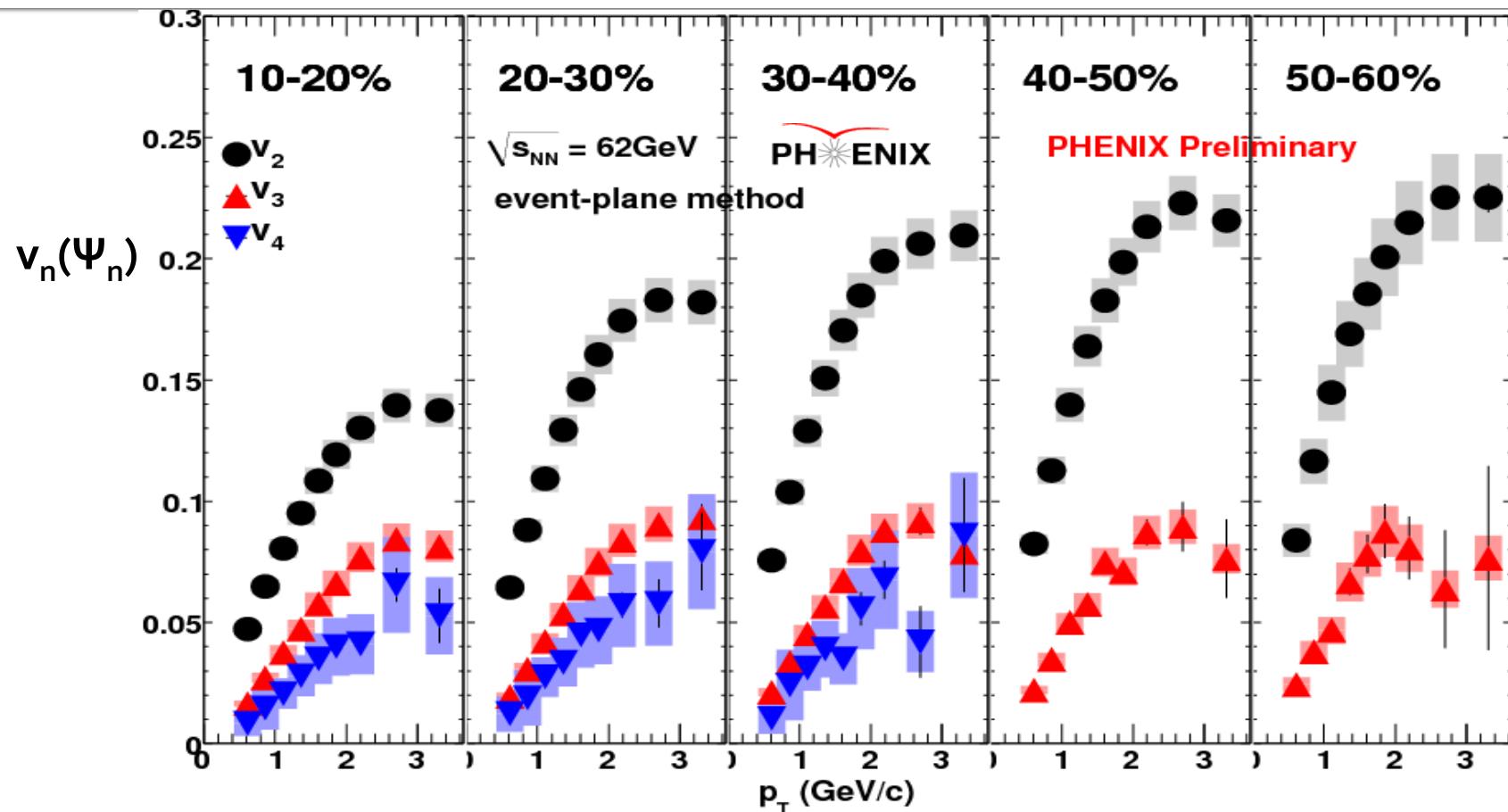
2PC gives the same flow results as EP method

Non-flow effect is absent/small



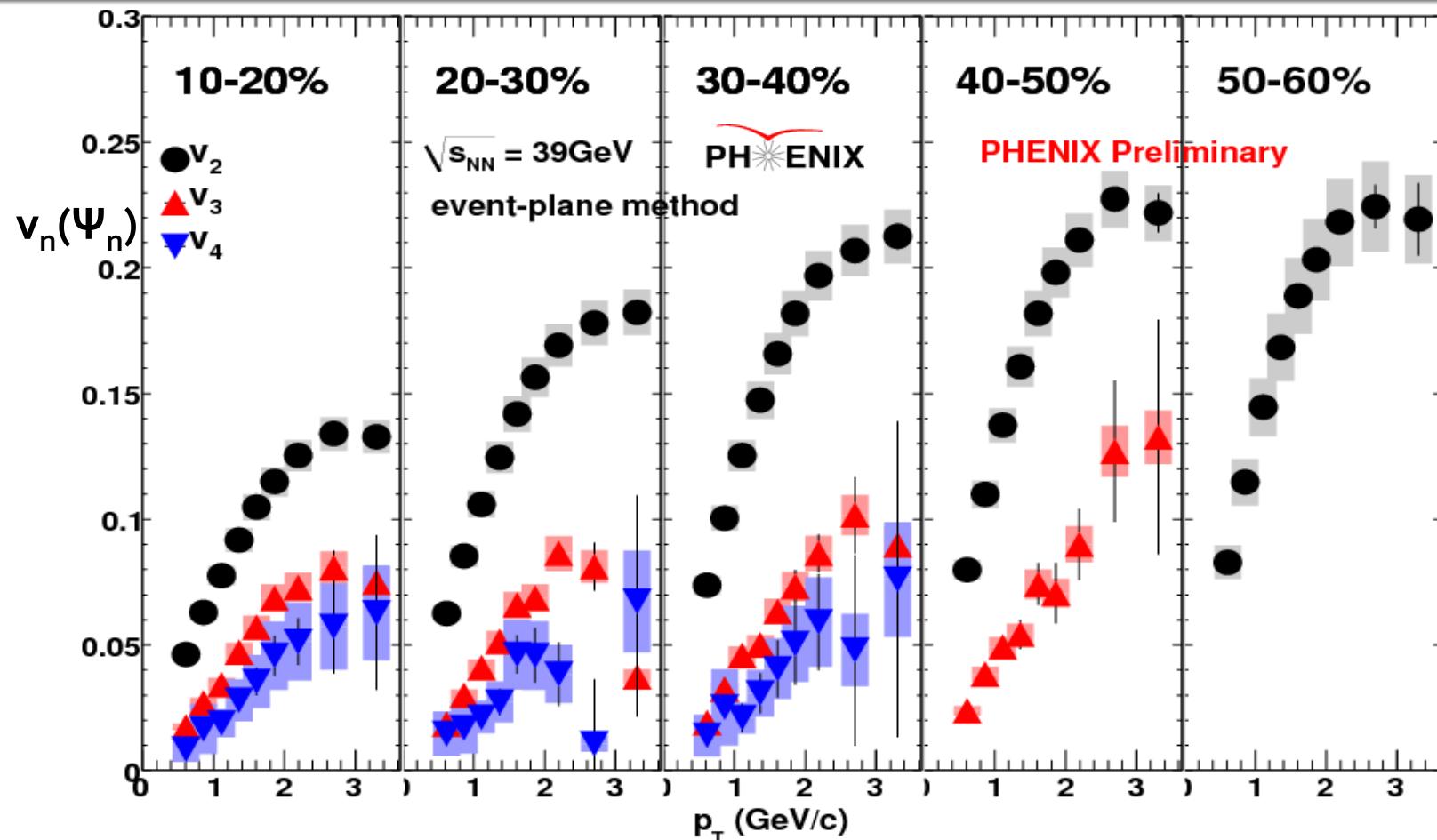
Flow Measurements $\nabla n\{\Psi_n\}$ at Low Energies

Charged Particle $V_n\{\Psi_n\}$ (62.4 GeV)



- Sizeable V_3 and V_4 (up to mid-central) are observed
- V_3 and V_4 show much weaker centrality dependence, not like V_2
- Similar trend as 200GeV(arXiv:1105.3928) observed in each V_n measurement

Charged Particle $V_n\{\Psi_n\}(39\text{GeV})$

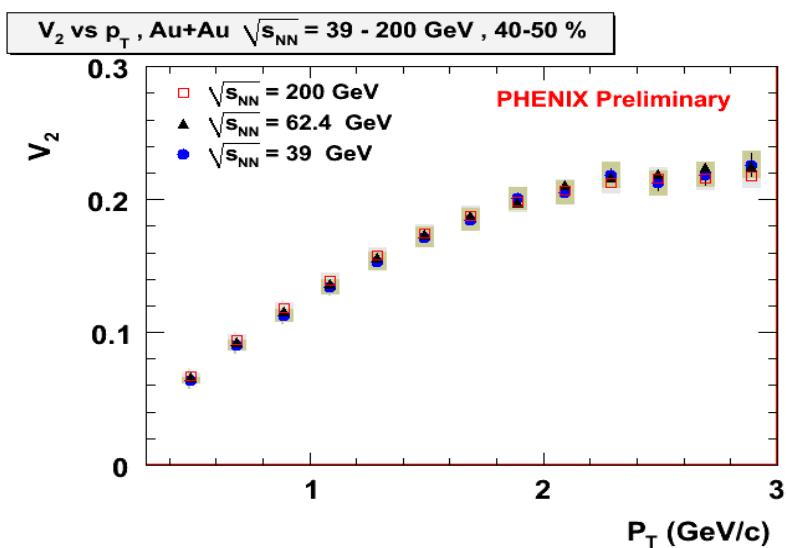
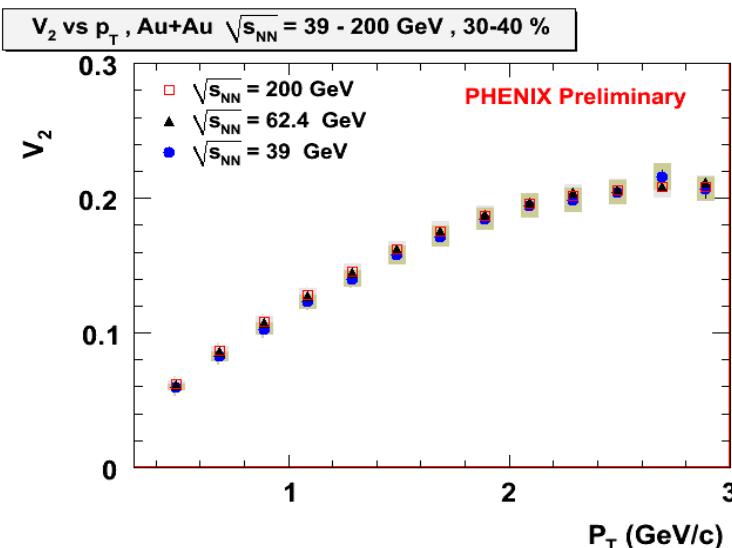
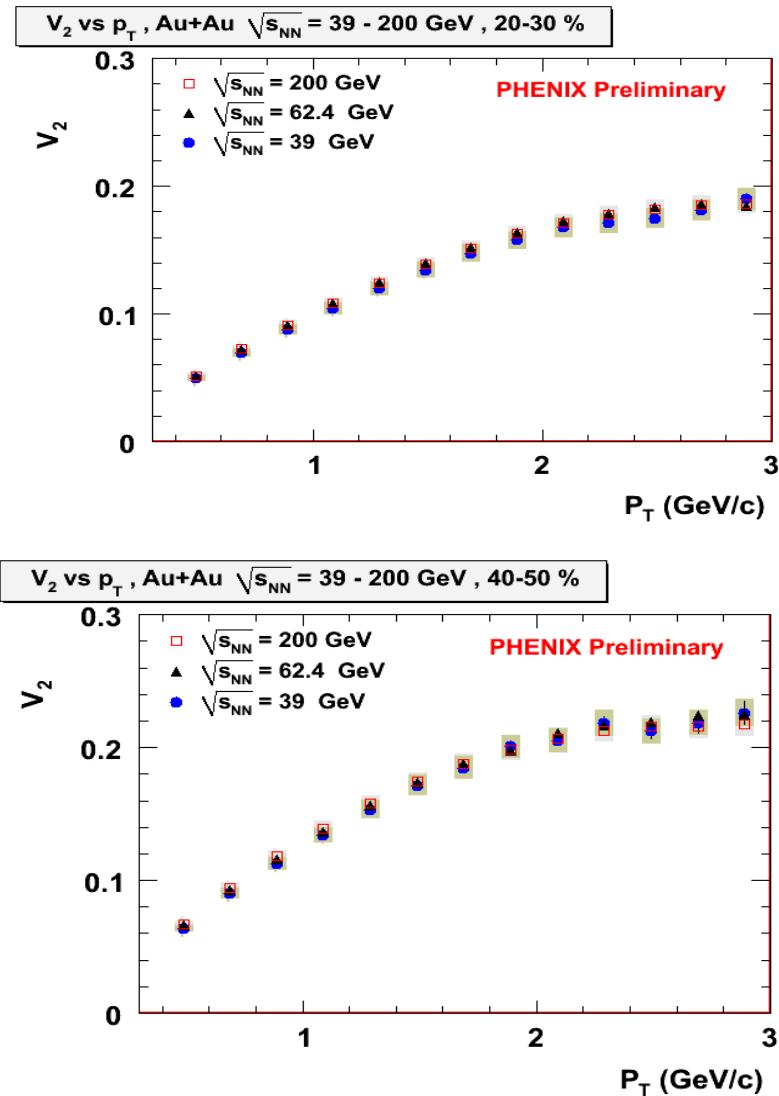
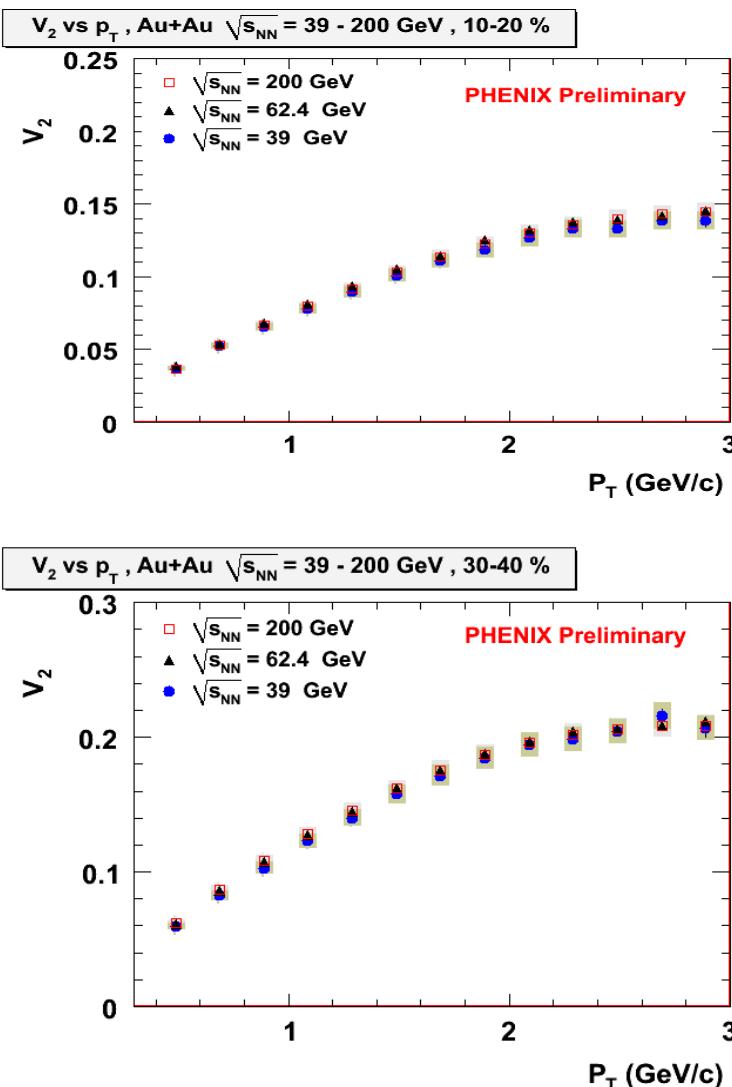


- Sizable V_3 and V_4 (up to mid-central) are observed
- V_3 and V_4 show much weaker centrality dependence,
- Similar trend as 200GeV(arXiv:1105.3928) in each V_n measurement



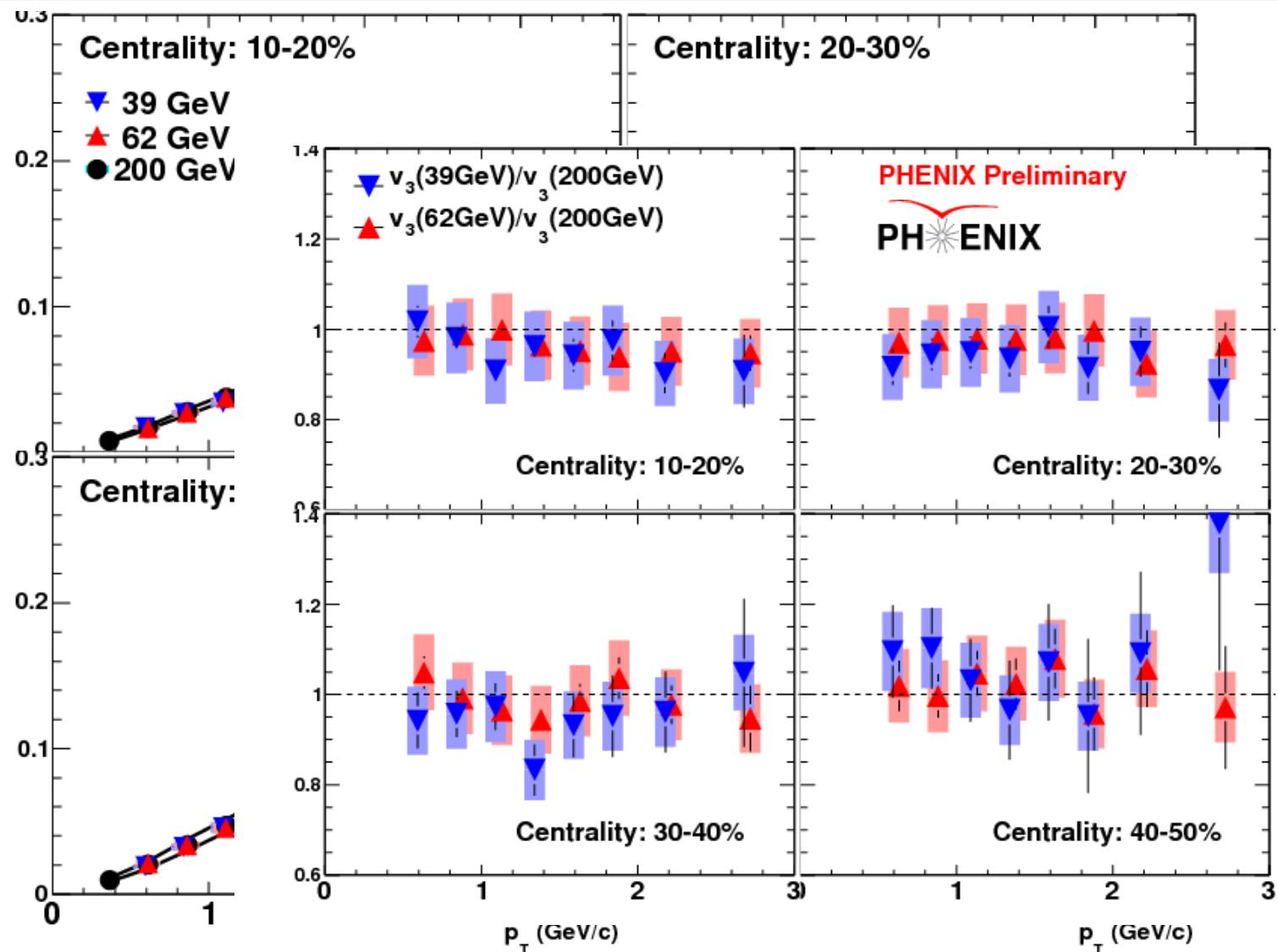
Energy Dependence of Flow Coefficients $V_n\{\Psi_n\}$

Energy Dependence of Charged Particle $V_2\{\Psi_2\}$



Differential $v_2(p_T)\{\Psi_2\}$ shows saturation in beam energy range 39GeV-200GeV

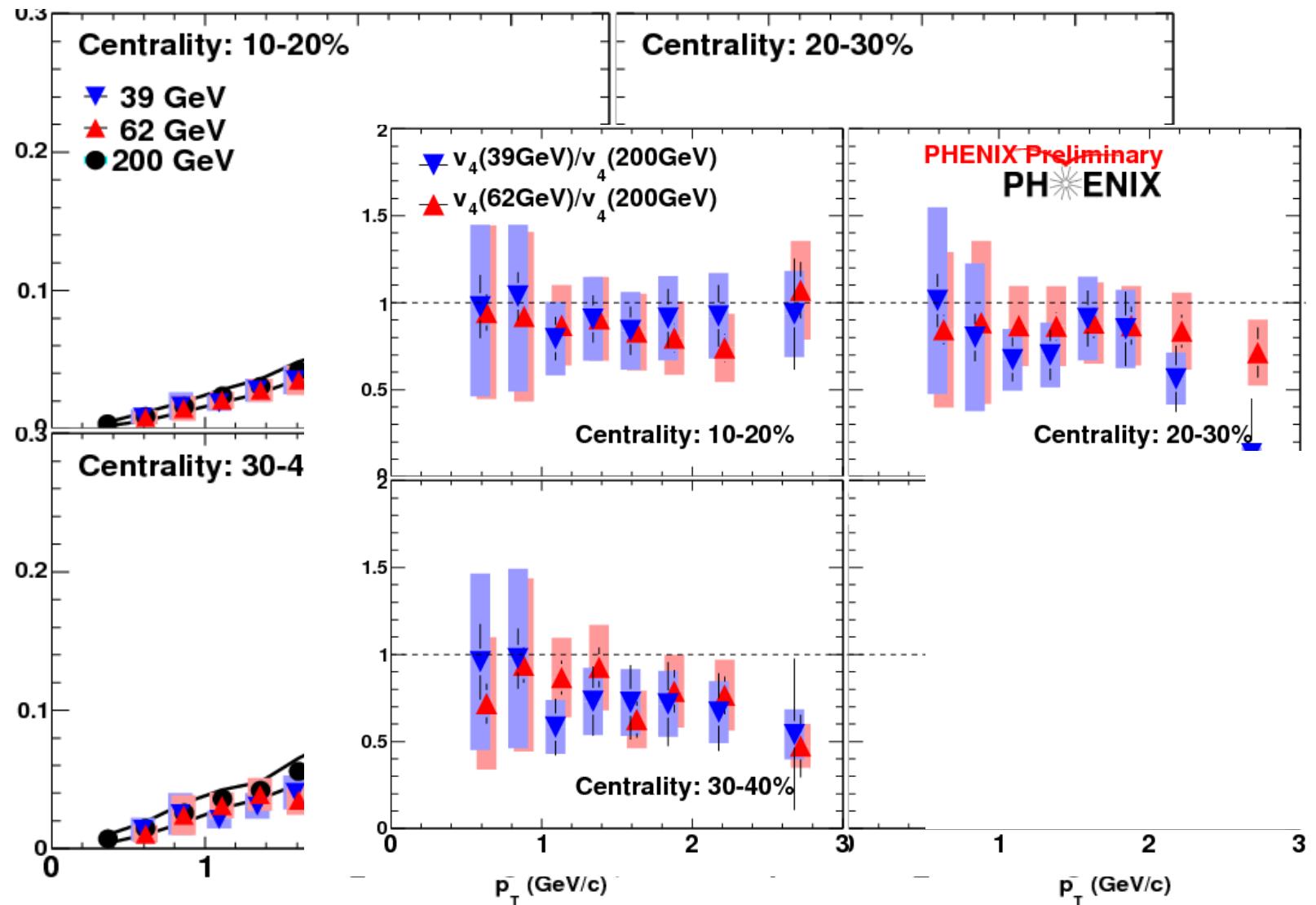
Energy Dependence of Charged Particle $v_3\{\Psi_3\}$



Differential $v_3(p_T)\{\Psi_3\}$ shows saturation in beam energy range 39GeV-200GeV

Workshop on Fluctuations, Correlations and RHIC Low Energy Runs , BNL, Oct 3rd, 2011

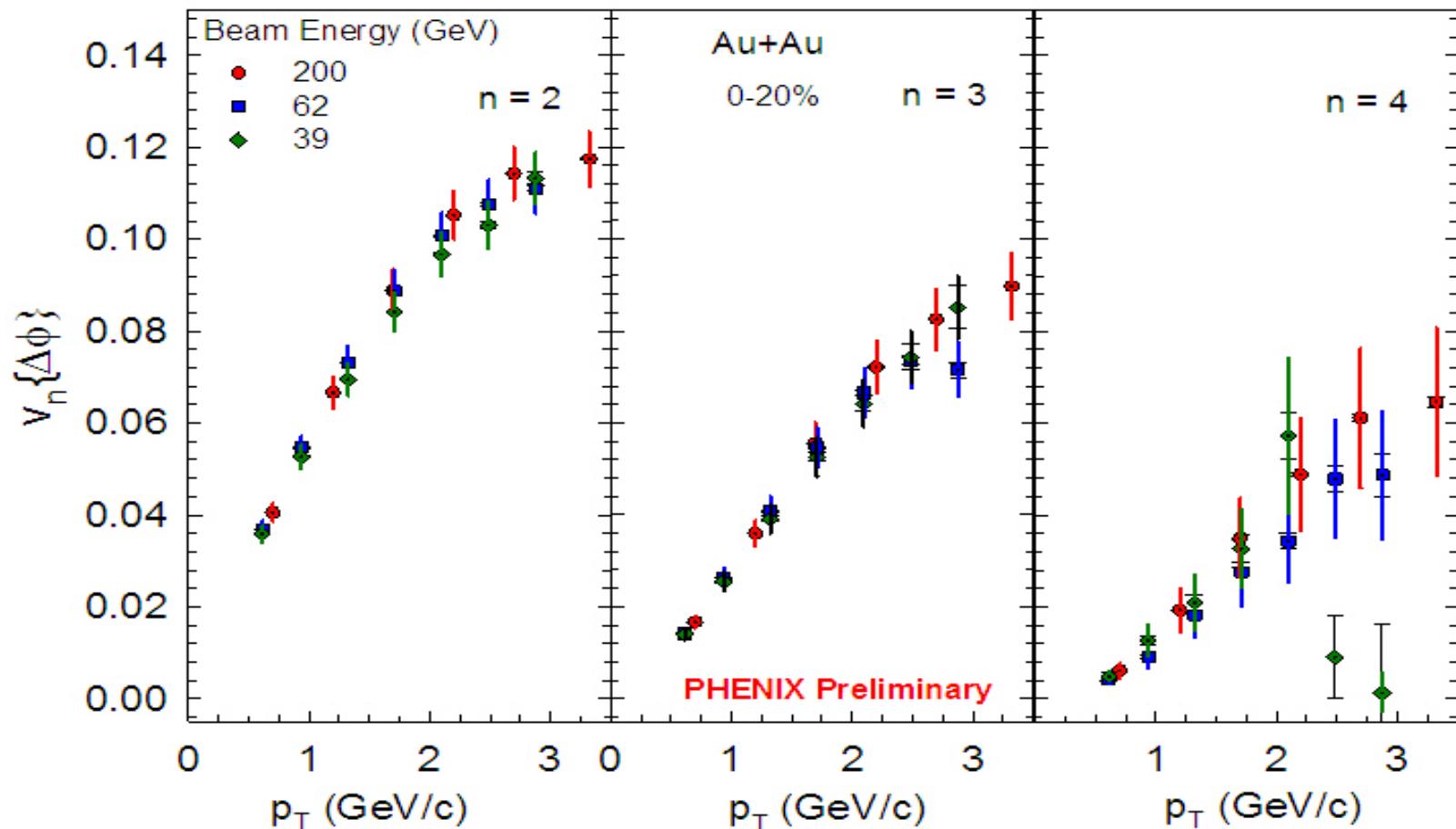
Energy Dependence of Charged Particle $V_4\{\Psi_4\}$



Differential $V_4(P_T)\{\Psi_4\}$ shows saturation within systematic errors as well.

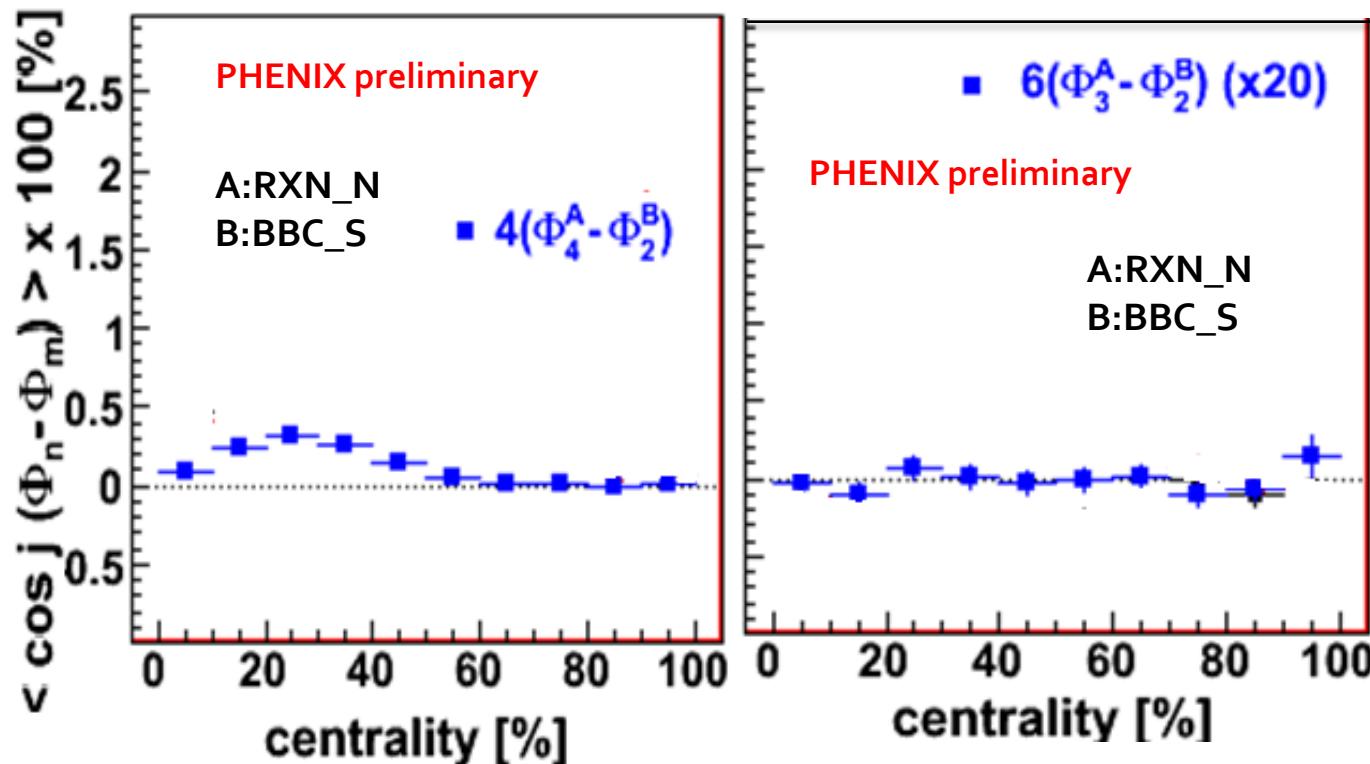
Workshop on Fluctuations, Correlations and RHIC Low Energy Runs , BNL, Oct 3rd, 2011

2pc Confirms Saturation



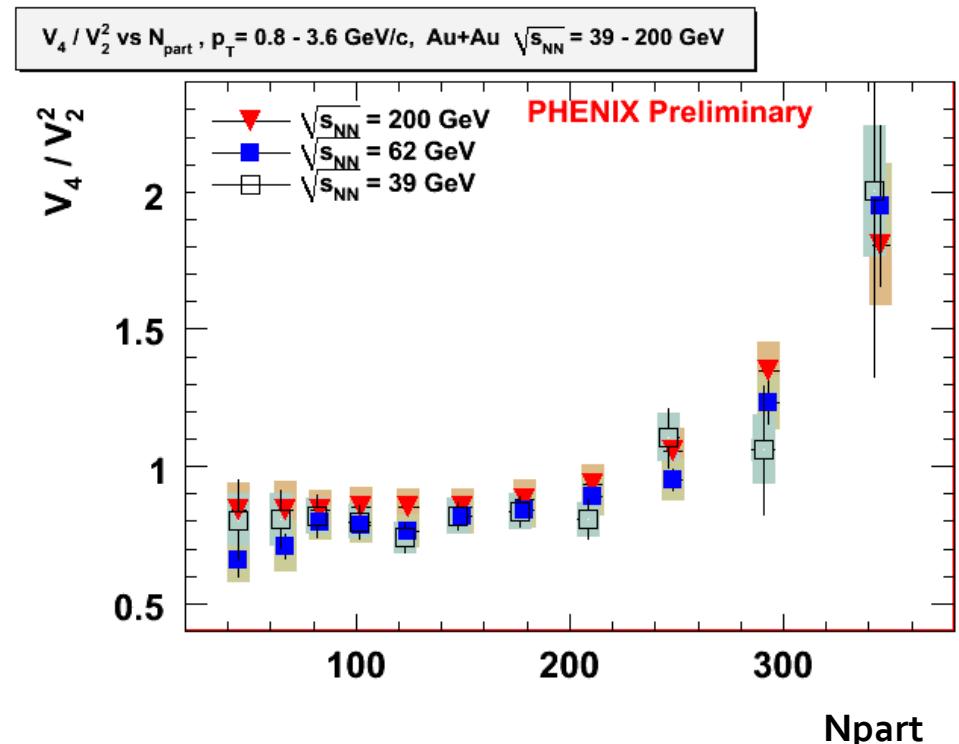
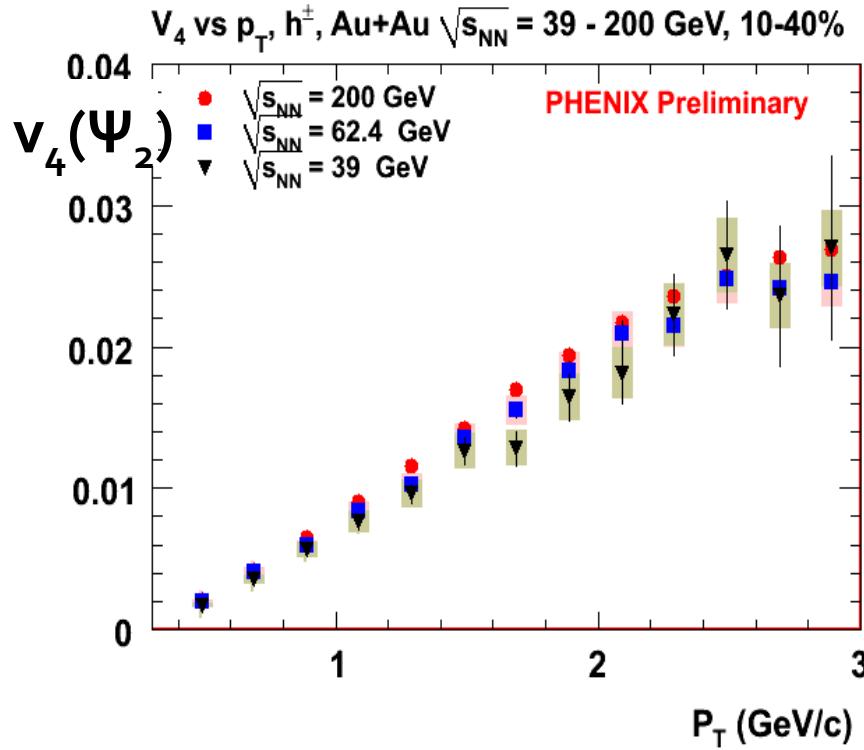
There is no dramatic change in the flow hydrodynamical behavior within the collision energy region 39-200GeV

Correlation between different order of R.P



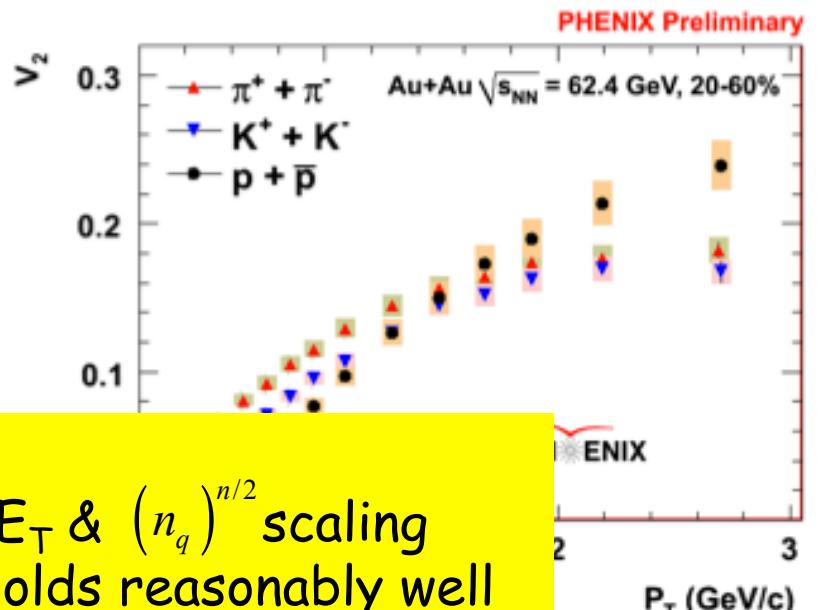
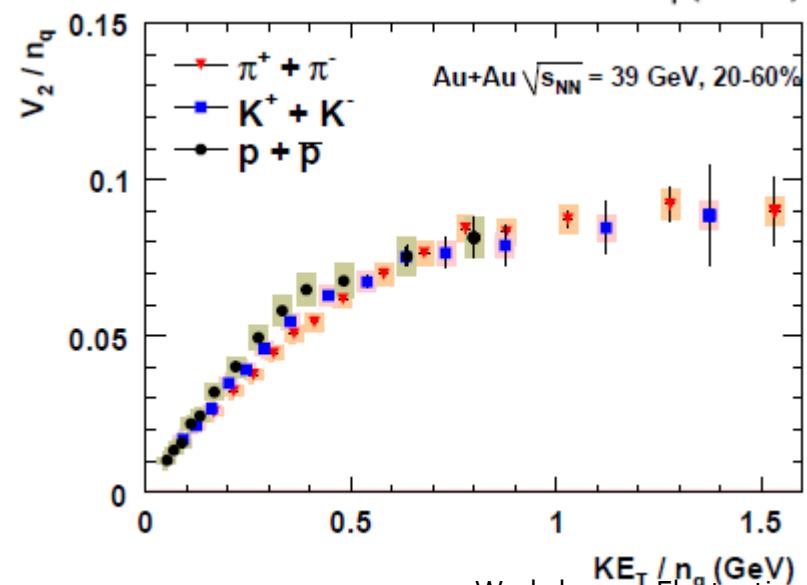
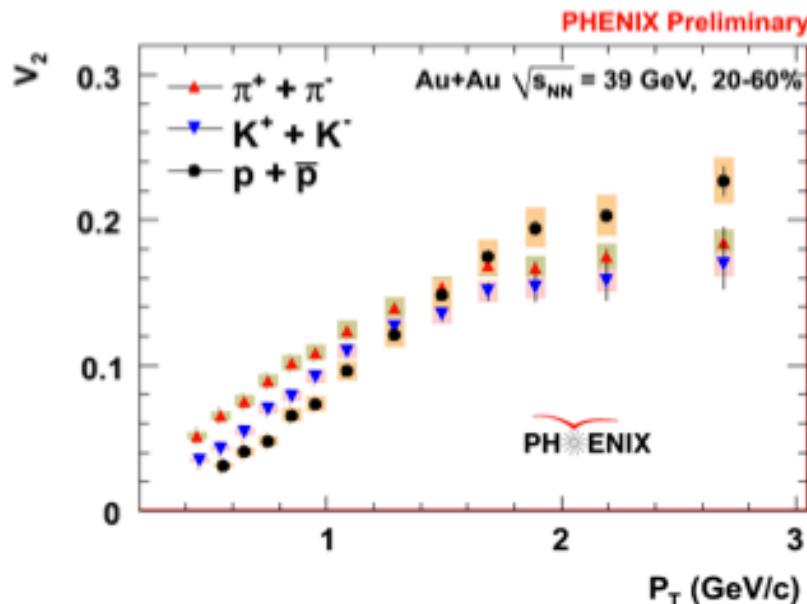
- As expected, no correlation observed between 2nd(even) and 3rd(odd) order R.P
- Measurable correlation observed between 2nd and 4th order of R.P

Mix-ordered Harmonics of Charged Particles, $V_4\{\Psi_2\}$

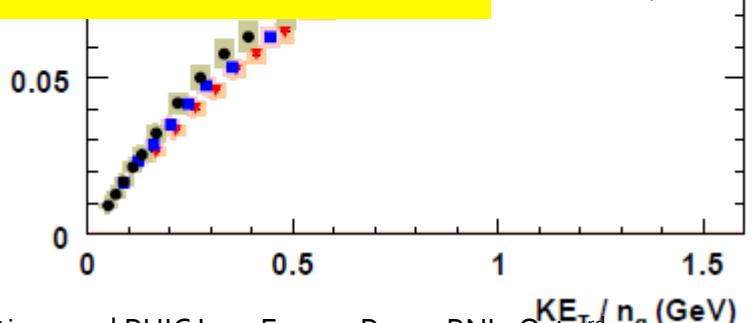


- Since Ψ_2 and Ψ_4 are correlated, we observe sizable $v_4(\Psi_2)$.
- Note : $V_4\{\Psi_4\}$ larger than $V_4\{\Psi_2\}$ (Phys.Rev.Lett.105:062301,2010) due to additional correlation in Ψ_4 - Ψ_2

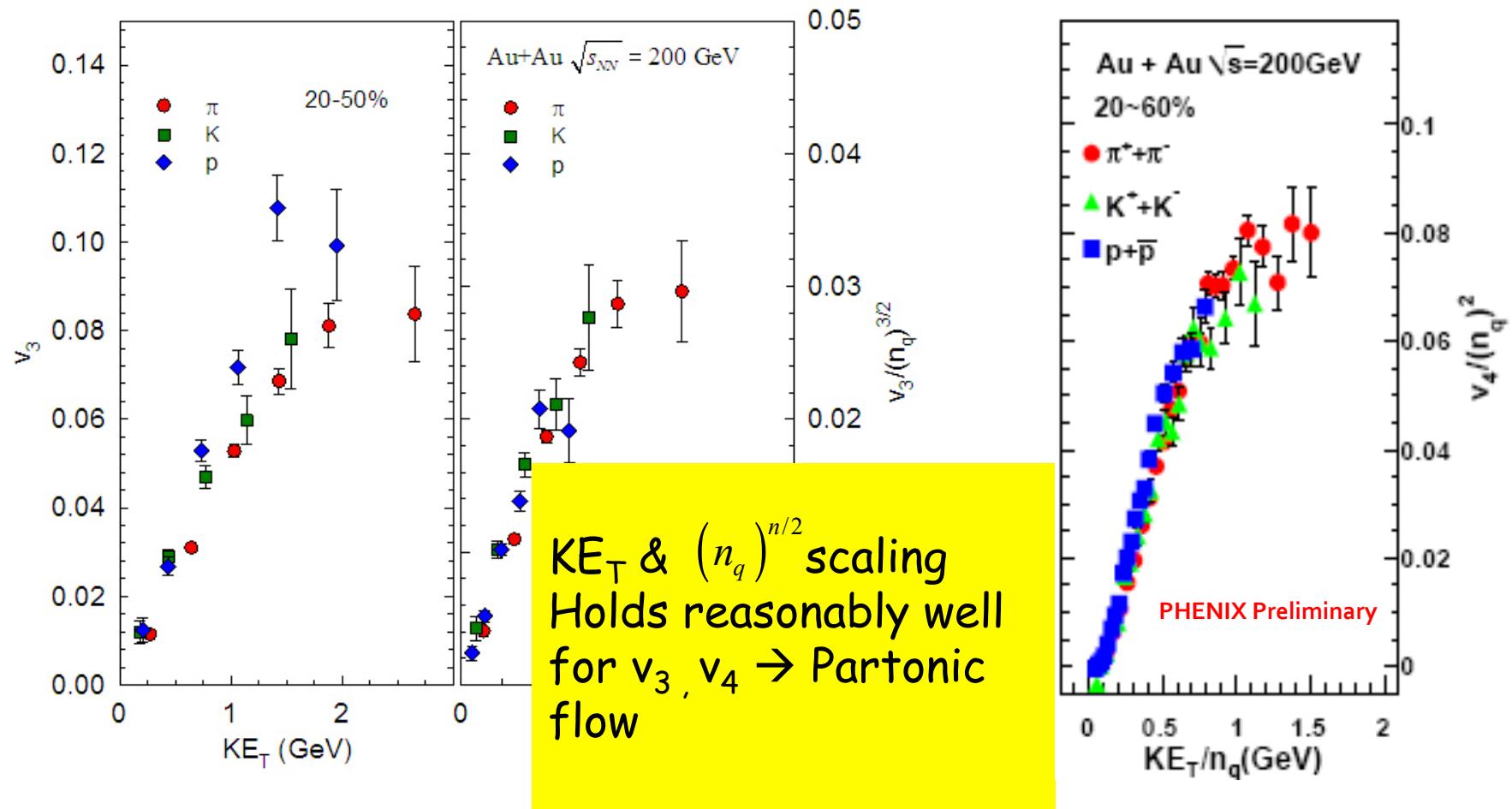
PIDed Hadron $V_2\{\Psi_2\}$ (39GeV , 62.4GeV)



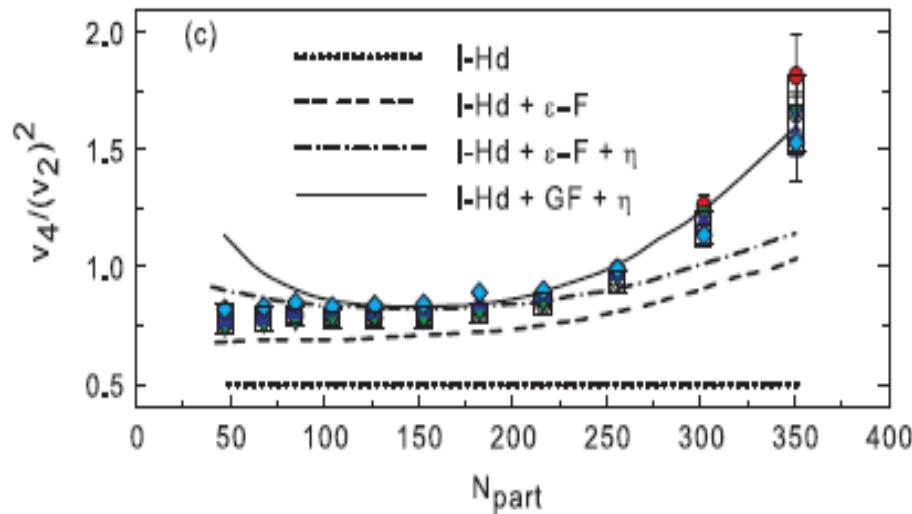
KE_T & $(n_q)^{n/2}$ scaling
Holds reasonably well
for v_2 at low beam
energies
→ Partonic flow



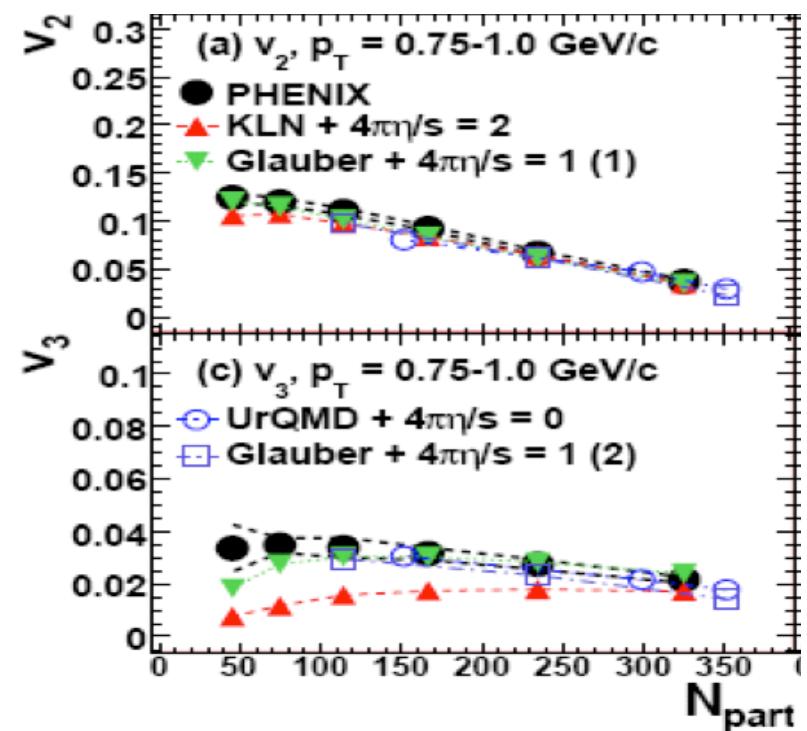
Consistency Partonic Flow Picture for Vn



Flow Measurements to Further Constrain Model



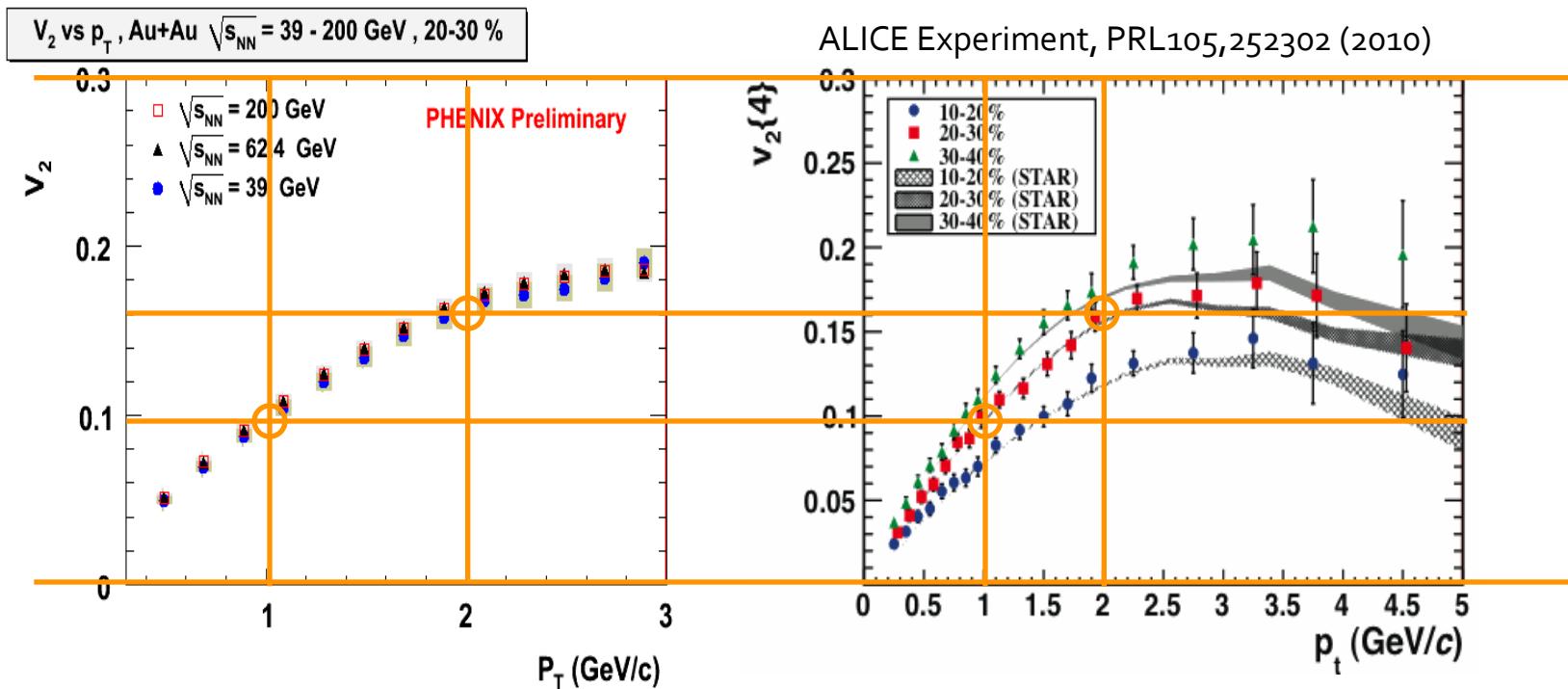
higher-order flow provides a constraint
for models of profile fluctuations



v_3 breaks the ambiguity between CGC vs.
Glauber initial conditions and η/s

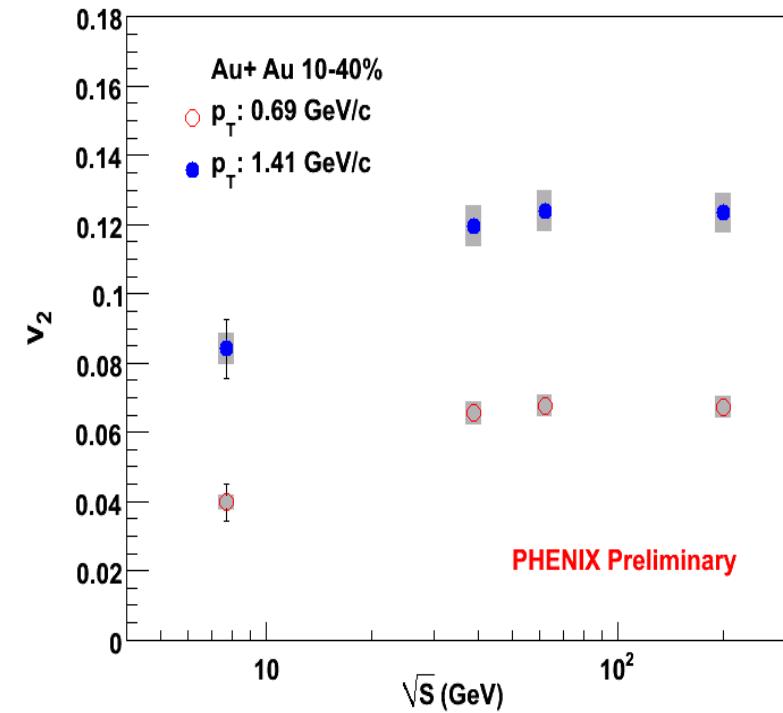
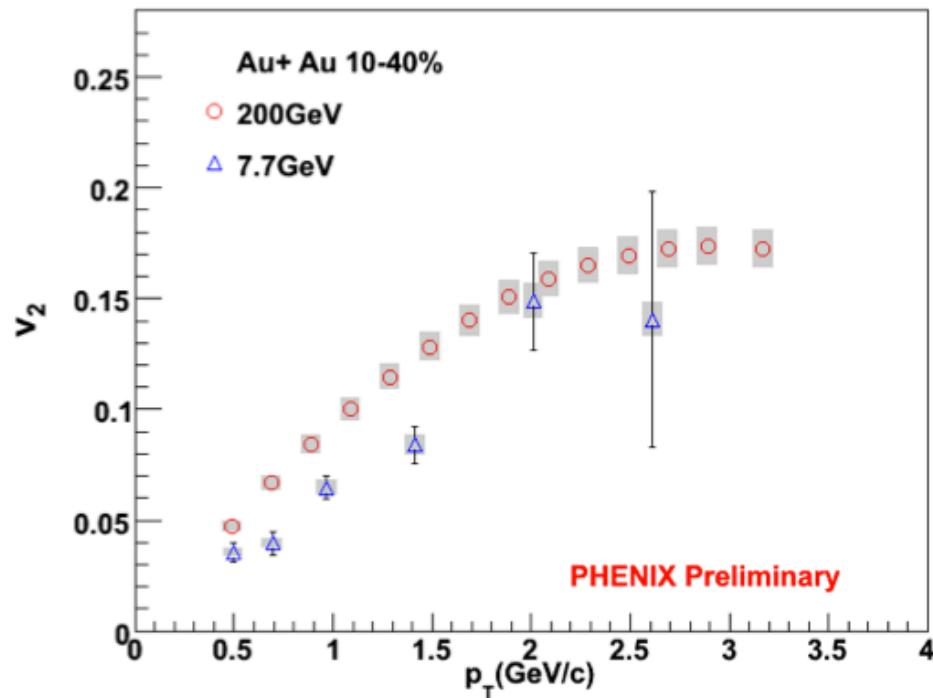
Comparison with LHC results

differential v_2 vs p_T from 39GeV to 2.76TeV



- Similar hydrodynamic behavior observed from 39GeV to 2.76TeV
- Almost perfect fluidity from 39GeV to 2.76TeV

Flow across broader energy range



Current measurements below 39GeV show drop of v_2 value

Possible transition between dominant partonic d.o.f to hadronic d.o.f occurs in the gap

Where transition is coming about in this transitional region?

Summary

- Significant and reliable higher order event anisotropy observed, at low beam energies
 - We extracted via both EP and 2P correlation methods
 - Consistent with initial geometrical fluctuation
- Almost perfect fluidity from 39GeV to 2.76TeV
- Nq scaling ansatz still holds down to 39GeV
 - Further confirm the flow is partonic at low beam energies
- Flow magnitude starts to decrease as the beam energy is below 39GeV which suggests possible transition from quark d.o.f to hadronic d.o.f might occur

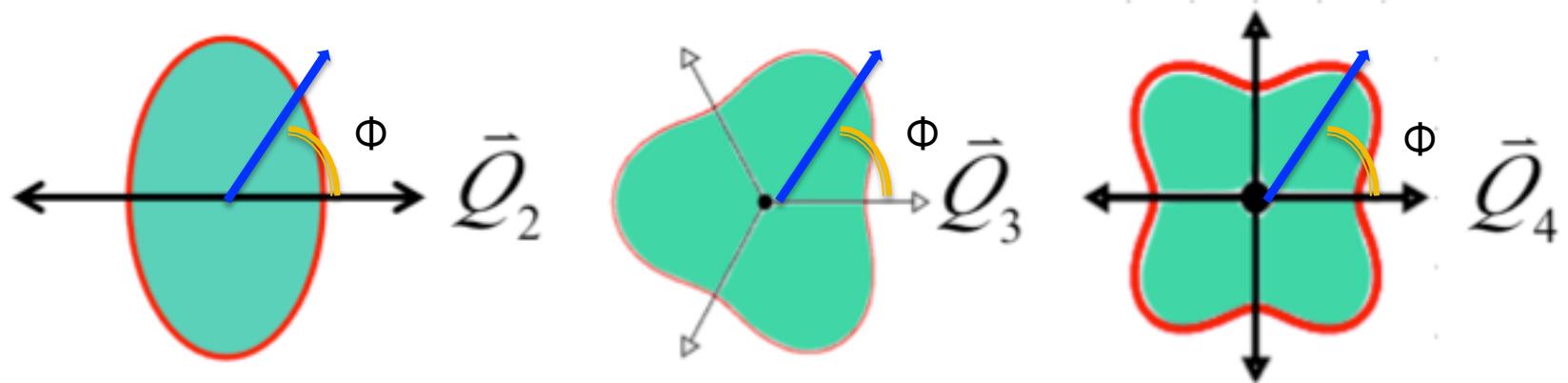
Thank you





Back up

Event Plane(E.P) Determination

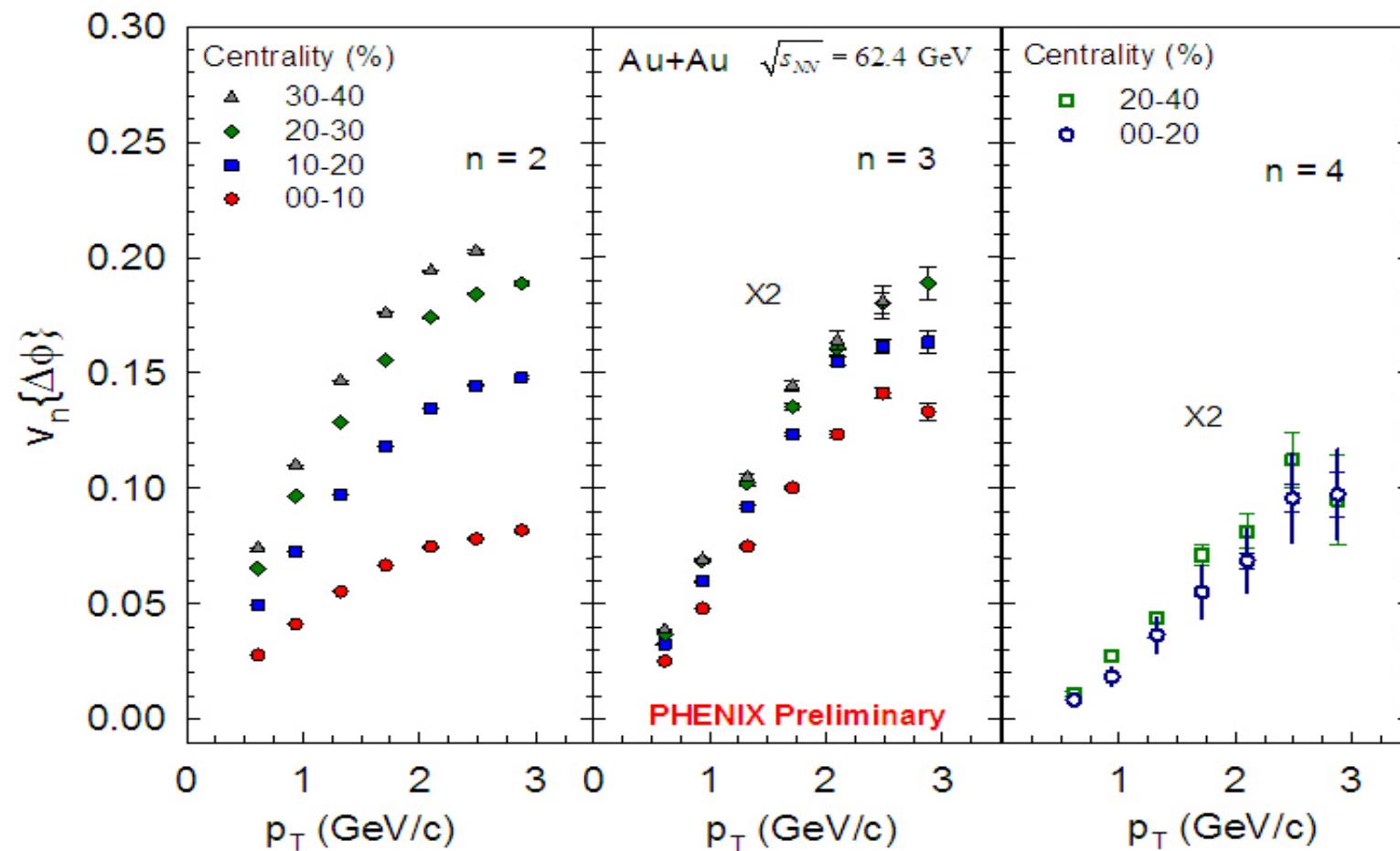


$$Q_{nx} = \sum_i w_i \cos(n\phi_i), Q_{ny} = \sum_i w_i \sin(n\phi_i),$$

- v_n^{obs} measured by correlation of tracks with n^{th} flow vector Q_n
- Followed by a resolution correction

$$v_n = \frac{v_n^{\text{measured}}}{\text{Res}\{\psi_n^{\text{EP}}\}} = \frac{\langle \cos n(\phi - \psi_n^{\text{EP}}) \rangle}{\langle \cos n(\psi_n^{\text{EP}} - \psi_n) \rangle} = \langle \cos n(\phi - \psi_n) \rangle$$

2PC Method (62GeV)



2PC Method (39GeV)

